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Optimization of window-to-wall ratio with sunshades in China low latitude region considering daylighting and energy saving requirements

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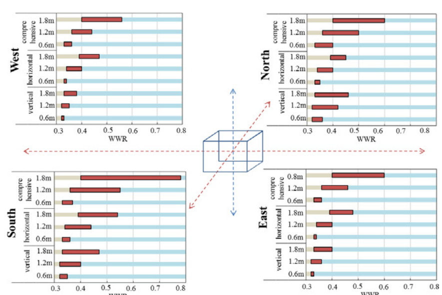
HIGHLIGHTS

- Optimization process of WWR for buildings in China low latitude area is proposed.
- Sunshade configurations are integrated in evaluating building performances.
- Optimal WWR ranges are found based on daylighting and energy-saving principles.
- Largest WWR could reach to 0.78 with comprehensive sunshade for south-facing units.
- Proposed design scenarios are verified and optimization process could be promoted.

GRAPHICAL ABSTRACT



Optimized WWR for all orientations with daylighting and energy requirements

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ABSTRACT

Daylight is a valuable resource with characters of both photometry and radiometry, and window-to-wall ratio (WWR) is a crucial building envelope element that decides the indoor luminous and thermal environments. Due to the traditional utilize of external shadings and lack of appropriate design standard for buildings in China low latitude region, this study proposes a workflow for optimizing WWR with sunshades by considering both daylighting performance and energy consumption. The reference WWR is firstly decided based on the requirements of daylighting standards by using Radiance for standard room without external shading, and the reference annual cooling load of the whole building is then calculated by EnergyPlus. A large number of cases with different WWRs and external shadings are calculated and energy-saving and daylighting performances are finally verified with reference case. The optimal WWR value range with different sunshades configurations in different orientations is that meets daylighting requirement while below reference annual cooling load. The results indicate that comprehensive sunshades have the best energy performance with the benefits of both horizontal and vertical ones. With a 1.8 m comprehensive sunshade, the lower threshold of WWR raises to 0.40 for meeting daylighting requirement, and the accepted upper threshold of WWR range for west, north, east and south-facing units could reach to 0.56, 0.6, 0.6 and 0.78 respectively. For designing a building with façade the same in all orientations, the largest WWR could be set as 0.7 for west-east buildings and 0.55 for south-north buildings with 1.8 m comprehensive sunshades. The scenario has been verified and this WWR optimization process could be applied to different buildings in other climate regions.

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1. Introduction

1.1. Daylight and facade design

Solar energy is a ubiquitous free source, and it has significant influence on indoor built environment. The unique spectral power distribution [1] offers people a specific luminous environment and affects non-visual effects on occupants' physiology [2] circadian rhythms [3] at the same time. Except for photometry characters, daylight brings solar heat gains [4] which transfer to building cooling load and may increase building energy consumption dramatically in radiometry characters [5]. Both two characters happen hourly and simultaneously [6], and daylight is therefore essential to people subjective satisfaction [7] and building objective energy consumption [8]. This has been attracting growing consciousness and interests for researchers and designers.

As a carrier of daylight, window system is generally considered as the crucial aspect for indoor luminous and thermal environments. Large aperture will bring more solar heat gains and also increase heat exchange as heat transfer coefficient of window is usually larger than wall. Daylighting performance will also be improved with larger transparent area [9]. However, in most hot and cold dominated regions, windows will leading a conflict performance between daylighting and energy performances. Therefore, appropriate WWR value should be carefully selected for a façade at the early design stage.

1.2. Window-to-wall ratio

Among all the elements involved in facade design, the window-to-wall ratio (WWR) – the ratio between the transparent area and total façade surface – is a parameter which has a deep impact on the balance between daylighting and energy [10]. WWR is firstly recognized as an influence factor for energy balance [11], which includes heating [12] and cooling energy use [13]. The impacts of WWR was also proved that adding windows could result in 180% increase in total cooling and heating energy consumption [14]. Pino et al. [15] confirmed a 100% WWR will bring 155 kWh/m^2 annual total cooling and heating demands in Chile, while the demand might decrease to 25 kWh/m^2 with 20% WWR. Grynning et al. [16] stated the windows outperform the opaque wall about heating and cooling demands in Norway by considering both thermal transmission and incident solar radiation. The WWR with single glazing material was also found to have the greatest impact on the environmental burden in life cycle [17], especially on north side [18]. Except for cooling and heating, lighting energy should be considered in the total energy consumption [19], as adequate daylight affected by WWR could decrease the use of artificial lighting [20].

With this viewpoint, the optimization of WWR is a complicated problem, and the optimal value is thus the best compromise of energy and daylighting performances. A systematic workflow for façade design was presented by Bueno et al. [8], and it focused on the functions of visual contact with the outside, daylight provision, solar heat and glare. Ochoa et al. [21] studied the suitability of WWR with combined optimization criteria of low energy consumption and high visual comfort. Goia et al. [22] studied optimal façade configurations for office buildings with integrated thermal and lighting simulations, and dynamic metrics (daylight autonomy [23] and useful daylight illuminance [24]) are adopted for assessing daylighting performance. Mangkuto et al. [25] investigated the influence of WWR, wall reflectance, and window orientation on various daylight metrics and lighting energy demand and the most optimum solution was found as a combination of WWR 30%, wall reflectance of 0.8, and south orientation. Feng et al. [26] studied on the influence of WWR for nearly zero energy buildings and the results showed impact level of different orientations' WWR on energy consumption order is east (west) > south > north.

1.3. Unique situation in China low latitude region

Climate condition has also been confirmed as a crucial factor on WWR optimization from fruitful researches [27]. According to ambient temperature amplitude and envelope U-value, seven US climate were adopted to study different maximum WWRs for each cities [28]. An optimal WWR in all sub-climates and orientations under European climate was generalized in a relatively narrow range: $0.23 < \text{WWR} < 0.31$ (converted from different WWR definition), and only south-facing units in a very cold or very warm climate will have WWR out of this range [29]. Different default scenarios of WWR for Japanese buildings were investigated in 10 locations, and ranges were provided for each regions [13]. Five typical Asian regions were also investigated and the optimized window system for each climate were decided [9].

The latitude of Chinese mainland spans a wide range, and the meteorological conditions are very complex. The China low latitude region, such as Nansha, still has a 20° gap in latitude from the Hainan province, and there is no appropriate building standard for any design currently. The annual temperature and humidity are high, solar radiation is strong all year around, and the air-conditioning period is long, which decides the cooling as the dominant energy end use. To reduce the solar heat, the use of external shading has become a necessary energy-saving method in low-latitude areas. It is important to notice the researches mentioned above did not include the utilization of sunshades.

As one of the façade elements, sunshades plays a vital role to lower the energy demands [30], decrease daylighting performance [31] and affect visual satisfaction. Daylighting and energy performance with automated interior roller shades are investigated by more and more researchers [32]. The implementation of model-based control for shading, lighting and HVAC operation minimized the energy use while satisfying glare constraints [33]. New shading devices are also proposed innovatively to reduce the overall energy consumption [34]. However, there is still a lack of analyses that include external solar shadings for building WWR design for both low-energy and livable buildings. In summary, the optimal WWR is remarkably decided by the combined influence of climate, insulation, façade configurations and presence of shading devices. Therefore, the overall influence of WWR and external shadings on thermal and luminous environment should be further studied.

1.4. Purposes of this study

This study aims to propose a workflow for optimization design of WWR by considering both energy consumption and daylighting performance. A typical hotel building in China low latitude region is selected as a case. External shading devices are involved in this façade study based on an actual hotel building, and optimized WWR value ranges will be given with different sunshade configurations in different orientations.

2. Methodology

The methodology adopted to generate optimal WWR value ranges for each orientations with different sunshades required a relatively large number of simulations. A hotel building in design stage is recruited as a typical building located in the China low latitude region as there is no other public buildings. The sequence of simulations is shown as Fig. 1 and optimization process can be schematized into the following steps:

(1) obtains minimum WWR by using Radiance for standard room without external shading based on the requirements of daylighting standards;
(2) calculates the reference cooling load of the whole building by adopting EnergyPlus based on the minimum WWR condition;

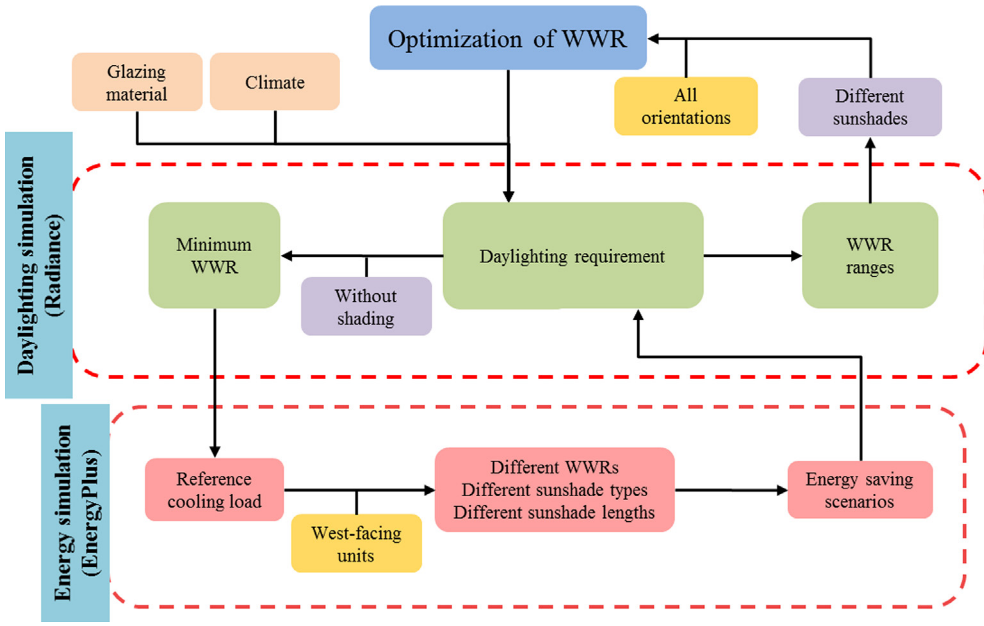

Fig. 1. Workflow of optimization in WWR.

(3) calculates the cooling load with different WWRs and external shading scenarios, and proposed possible WWR range by achieving energy saving compared with reference case;
(4) verifies daylighting performance again within the energy-saving scenarios, and proposed the final WWR range for each orientation.

2.1. Climate condition and building modelling

The standard weather data of Qionghai is set as the reference outdoor condition in this study. Qionghai is located at 19.23° north latitude and 110.47° east longitude, and it belongs to the low latitude area. The annual temperature ranges from to 10 °C and 33 °C, and average temperature in the area is 24 °C. The annual average relative humidity is above 80%, and its total annual radiation is about 5400 MJ/m^2·a as it is close to the equator. Therefore, cooling load is the only consideration in the energy analysis.

The hotel building model has 3 storeys and 48 rooms with a total construction area of 2050 m^2 according to designed condition, as shown in Fig. 2. Rooms are all standard rooms, with the length, width and height as 6.9 m, 3.9 m and 3.9 m respectively and symmetrically arranged on both sides of the corridors. To simulate energy and daylighting performances, envelope materials are adopted as the settings in Table 1. Owing to the influence of the glazing is not considered, the ordinary single-layer glass is selected. The average visible transmittance at normal incidence is 0.753, while the average solar transmittance at normal incidence is 0.708.

Table 1
Envelope materials.

Building envelope	Layers	Total heat transfer coefficient W/(m^2·K)
Roof	Cement mortar Microstone concrete Cement mortar Cement expanded perlite Extruded polystyrene foam insulation board Cement mortar Reinforced concrete	0.503
Exterior wall	Cement mortar Autoclaved sand-lime brick Styrofoam Autoclaved sand-lime brick Cement mortar	0.707
Exterior window	Single-layer glass	5.74 (SHGC 0.782)

2.2. Simulation set-up

In order to simulate the real condition of the rooms, two well-known and validated software are adopted to reproduce daylighting and

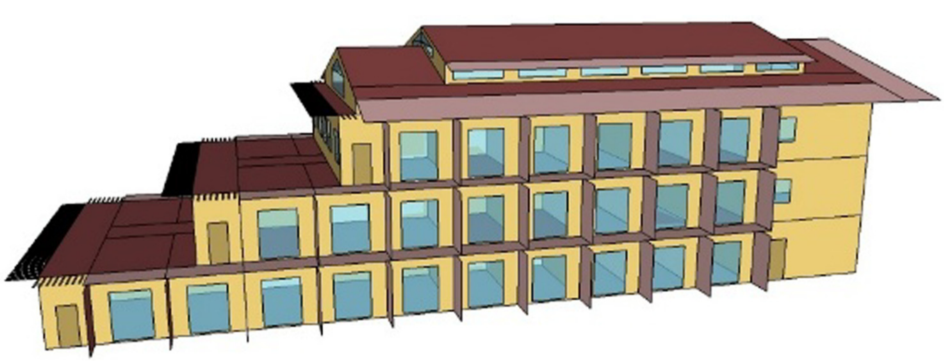

Fig. 2. Simulation model of the designed hotel.

energy performances. Radiance uses ray-tracing algorithm and most of the daylighting software use it as the engine. The worst condition (overcast sky) is considered in daylighting simulation and static metric is enough for WWR optimization. Therefore, climate-based daylight modeling and dynamic daylight metrics are not essential in this work. EnergyPlus is an well validated energy simulation engine [35] supported by Lawrence Berkeley National Laboratory based on the state-space techniques and due to the cooling-dominant climates in low China low latitude region, only annual cooling load is calculated by EnergyPlus.

2.2.1. Daylighting performance

China still adopts Daylight Factor (DF) in describing qualified daylighting area in current daylighting standard [36], while dynamic metrics have not been evaluated well for application. Radiance is used for simulating daylighting performance in this study, and DF is adopted as the indicator which stands for the worst indoor daylighting condition. In Chinese design standards for green buildings [37], an item requires the 75% of the indoor floor area should reach the DF requirement (2% for hotel building) at working level (shown as Eq. (1)). Therefore, this item is treated as the standard in this study to evaluate whether the daylighting performance meets the requirement or not.

$$\frac{Floor\ \ area\ \ where\ \ DF \geq 2\%}{Total\ \ floor\ \ area} \geq 75\% \tag{1}$$

The simulation used ray-tracing algorithm, and CIE standard overcast sky is adopted as sky model. The indoor illumination plane is set at the height of 0.8 m, and the mesh was drawn with 6129 grids in each unit.

2.2.2. Energy performance

Heat balance method is adopted to calculate the cooling load for the whole building [38]. The heat balance equation for internal wall face and indoor air are shown as Eqs. (2) and (3) respectively.

$$q_i(n) + \alpha_i^c[t_r(n) - t_i(n)] + \sum_{k=1}^{N_i} C_b \varepsilon_{ik} \varphi_{ik} \left[\left(\frac{T_k(n)}{100}\right)^4 - \left(\frac{T_i(n)}{100}\right)^4 \right] + q_i^r(n) = 0 \tag{2}$$

$$\sum_{k=1}^{N_i} F_k \alpha_k^c [t_k(n) - t_i(n)] + [q_1^c(n) + q_2^c(n)] + \frac{L_a(n)(c\rho)_a[t_a(n) - t_r(n)]}{3.6} - HE_s(n) = V(c\rho)_r \frac{t_r(n) - t_r(n-1)}{3.6 \times \Delta\tau} \tag{3}$$

where $t_r(n)$ is indoor air temperature [°C]; $t_i(n)$, $t_k(n)$ are inner surface temperatures of the i-th and k-th building envelope [°C]; α_i^c is the convective heat transfer coefficient of the inner surface of i-th envelope [W/m^2·°C]; C_b is black body radiation constant, equal to 5.67, [W/m^2·°C]; ε_{ik} is the system blackness between the inner surface i and k; φ_{ik} is the radiation angle of the inner surface i to k; N_i is the total number of inner surfaces; $q_i(n)$ is the heat flux obtained from the inner surface i due to the temperature difference between the two sides [W/m^2]; $q_i^r(n)$ is the direct solar heat obtained of the inner surface i; F_k is the area of inner surface k [m^2]; $q_1^c(n)$ is the convective heat from illumination, human sensible heat and equipment at time n [W]; $q_2^c(n)$ is the heat consumed by the evaporation of moisture at the time n [W]; $L_a(n)$ is air infiltration rate at time n [m^3/h]; $(c\rho)_a$ is the heat capacity of air [KJ/m^3·°C]; V is room volume [m^3] and $HE_s(n)$ is the sensible heat of air conditioning system at time n [W].

Using these two equations, the cooling load and the thermal condition of the room could be obtained. If the indoor temperature $t_r(n)$ is constant, the sensible heat is the room cooling load. Based on the regulation in Energy saving standard [39], the room temperature is set as 25 °C for air-conditioning, which is working all the year around. Since the temperature difference is smaller than 10 °C, the corridor is not equipped with air-conditioning. The humidity in the low latitude

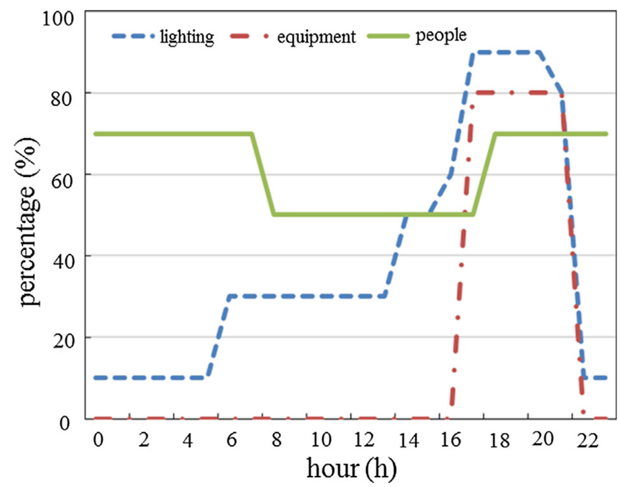

Fig. 3. Hourly schedules of lighting, equipment and people indoor.

area is tested as 65% for most time and air infiltration is considered as 0.5 time per hour. As the target building is still in the design stage, the occupancy, lighting and equipment schedules are set based on the regulation (Fig. 3). The lighting and equipment power densities are set as 7 W/m^2 and 15 W/m^2 respectively. Rooms are all standard rooms for two people and fresh air volume is set as 30 m^3/h for each person.

2.3. Cases set-up

As the units in the hotel building only face to two orientations, it is essential to study the performance based on the whole building. In step 1 and 2, the minimum WWR is decided by the daylighting standards, and nine cases are first set with different WWRs from 0.1 to 0.9. After the referenced WWR and cooling load are simulated and calculated, more cases are built to study the influence of external shadings. Except for WWR and orientation, energy performance differs much when considering sunshades scenarios. In this case, three kinds of sunshade configurations (Fig. 4) with three different dimensions are modelled in the target building facing 4 different orientations with several WWRs from reference value to 0.9. In this way, there will be totally more than 252 combined cases for the whole building. For each combination, the daylighting performance energy performance will be simulated by Radiance and EnergyPlus respectively.

3. Results

3.1. Baseline of WWR

CIE overcast sky model is isotropic in all directions, so the daylighting performances are the same in each units facing different orientations. In this case, DF value is only influenced by window position, WWR and sunshades. The minimum WWR can only be obtained with no shading device, and the window will be designed in the middle of the external wall in square shape. The percentage of the qualified floor area could then be simulated with different WWRs, and the results are shown in Fig. 5.

As seen from Fig. 5b, daylighting performance improves with the increasing of WWR. The percentage of qualified area increase sharply when the WWR below 0.3, which indicates the window is so important for daylighting and no matter how small it is. The percentage continues increase with a complicated curve, which may results from the calculation area excluded the washroom from the standard room (Fig. 5a). The qualified area becomes steady as it already reach a high level after the WWR grows to 0.7. To meet the daylighting requirement, WWR should reach 0.32 to guarantee 75% of the whole room area have the DF with 2%. Therefore, the minimum WWR is selected as 0.32, and the

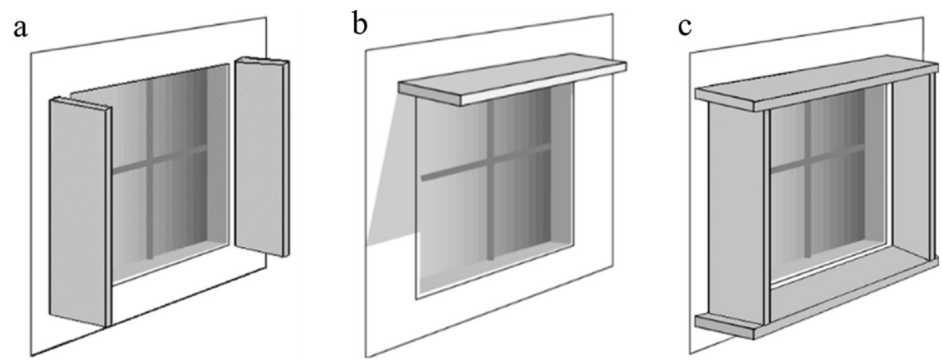

Fig. 4. Configurations of external shading: (a) vertical; (b) horizontal; (c) comprehensive.

reference energy consumption of the whole building can be calculated under this circumstance.

3.2. Baseline of cooling load

The main orientation is defined as the façade with building entrance. Due to the units in designed building facing to two opposite orientations, the cooling loads under different orientations should be different but maybe very close. The baseline of building cooling load under each main orientation is calculated when all units having reference WWR (0.32). The results of reference annual cooling loads for all orientations are 155.3 kWh/m^2 for east, 155.0 kWh/m^2 for west, 140.4 kWh/m^2 for south and 140.2 kWh/m^2 for north. From the results, the units facing west and east will obtain more solar heat than those facing south and north. Therefore, the main orientation of west and east will have a similar annual cooling load, which is 15 kWh/m^2 higher than the other two orientations. The reference cooling load for each orientation have been confirmed, and the annual cooling load with different WWRs could be calculated by EnergyPlus. The proposed scenarios for WWR are all modified on the main orientation, and the results are shown in Fig. 6.

It can be seen from the result that the cooling load increases and shows a linear relation with WWR for all orientation. This relation is confirmed by the linear regression (R^2 > 0.99), which indicates the load differs steadily with WWR changing for each orientation. Since window will receive a certain amount of radiation and convection heat per unit area, while the wall receive a certain amount of convection heat per unit area, it could be explained that the load will change with the difference when using the same area of window to replace the wall, which is shown as the slope of the linear line.

From the regression result, the slope of the west has the largest value, which indicates the annual cooling load will increase 6.9 kWh/m^2 with WWR increasing every 0.1. The cooling load increases less for east and south orientations and it increases least for north. This trend is

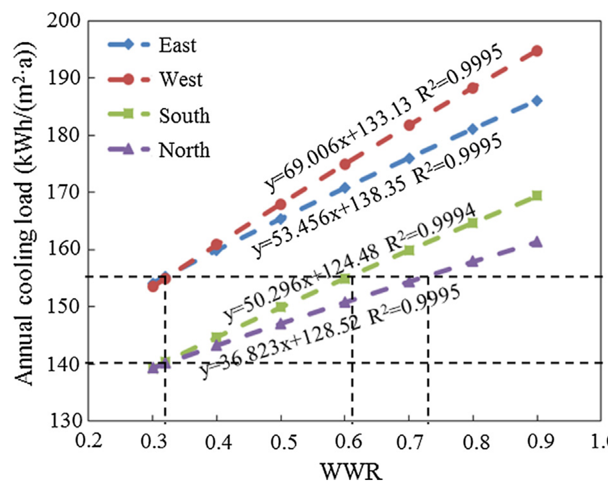

Fig. 6. Effect of WWR on the cooling load.

the same with solar heat gain in each orientation, and it could be concluded that the building cooling load in this low latitude area is much influenced by solar radiation.

3.3. Comprehensive scenarios of sunshades and WWR for energy-saving requirement

Based on the result from last section, the units facing west receive the most solar radiation, which affects the cooling load most. In this case, the optimization process of WWR with sunshade scenarios will be illustrated by the west-facing units.

3.3.1. Cooling loads under different WWRs and sunshade configurations

To evaluate the energy performances of the scenarios with different

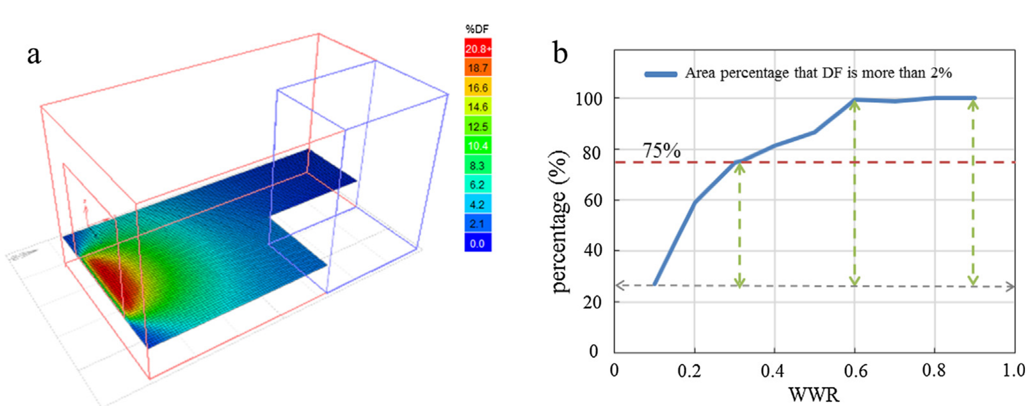

Fig. 5. The impact of window-to-wall on the DF value: (a) simulation result; (b) percentage of qualified area.

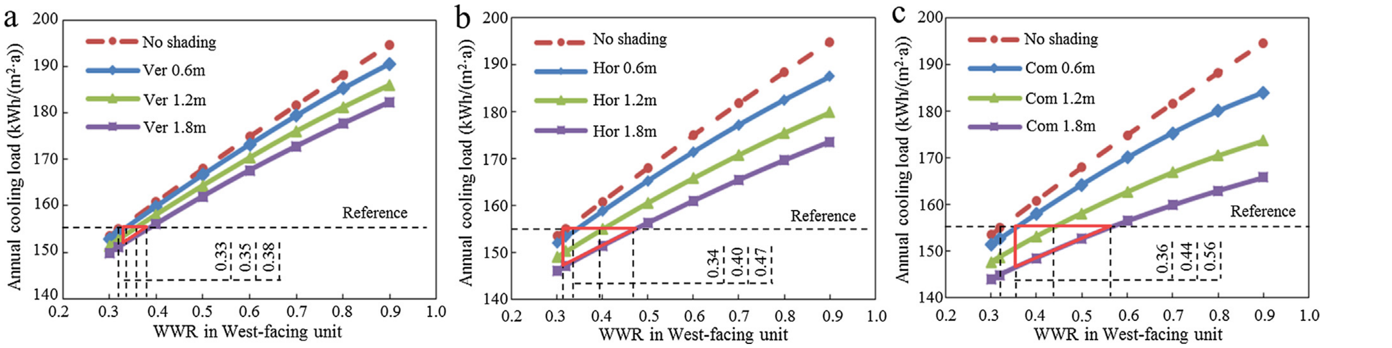

Fig. 7. Cooling loads under different WWRs and sunshade configurations: (a) vertical sunshade; (b) horizontal sunshade; (c) comprehensive sunshade.

WWRs and sunshade configurations, 72 cases are built according to principle in Section 2.3. The energy performance of all scenarios with vertical sunshade, horizontal sunshade and comprehensive sunshade are shown in Fig. 7a, b and c respectively. The reference energy performance without shading is also shown with dotted line.

From the result, it can be seen that external shadings will decrease cooling load, and the length of the sunshades have a positive shading effect. With the same length, horizontal sunshades have better performance than vertical ones in blocking solar radiation and decreasing cooling load. However, comprehensive sunshades have the best energy performance with the benefits of both horizontal and vertical ones. The largest energy saving of comprehensive sunshade with 0.9 WWR could reach to 30 kWh/m^2 out of 194 kWh/m^2.

3.3.2. Shading performance with reference WWR

Configuration of sunshade have influence on decreasing building annual cooling load, the energy saving performance for different scenarios with reference WWR are shown in Fig. 8.

From the result, the length of the sunshade has a positive influence on energy saving, and the comprehensive sunshade with 1.8 m length has the largest saving rate of 6.5%. This value stands for energy saving rate of the whole building, which means the units with sunshade save more energy. It can also be concluded from the figure that energy saving rate of comprehensive sunshade is not equal to the horizontal ones plus vertical ones at the same length. This could be explained as the savings are mostly influenced by shading area on windows, which is also related to sun path.

3.3.3. Maximum WWR with energy saving requirement

With the same reason of sun path, the increasing of cooling load with different WWRs does not show a linear trend (Fig. 7). With the increasing of the WWR, the increased load could not be offset by sunshades. Based on the energy saving requirement, maximum WWR scenario should use less energy than the reference case, and the limited values with different sunshades are summarized in Table 2.

Table 2
Maximum WWR under energy saving requirement for west-facing units with sunshade.

	Length of the sunshade (m)			
	0	0.6	1.2	1.8
Vertical sunshade	0.32 (reference)	0.33	0.35	0.38
Horizontal sunshade		0.33	0.34	0.47
Comprehensive sunshade		0.36	0.44	0.56

As seen from the table, the units with longer sunshade could be provided with larger windows, but vertical sunshade does not affect much. The comprehensive sunshade with 0.6 m length have the same energy performance with a 1.8 m vertical sunshade. Compared with the reference value 0.32, the accepted WWR could reach to 0.56 for the units with 1.8 m comprehensive sunshades. However, the energy saving scenarios are not enough for deciding WWR range as the daylighting performance may decrease with the different configuration of sunshades.

3.4. WWR range with daylighting requirement

In order to choose appropriate WWR for buildings, daylighting performances should be further checked among the energy saving scenarios. More cases are built and daylighting performance are evaluated by requirements with different sunshade configurations. The minimum WWRs are calculated and shown in Fig. 9.

To guarantee 75% floor area with daylight factor more than 2%, the

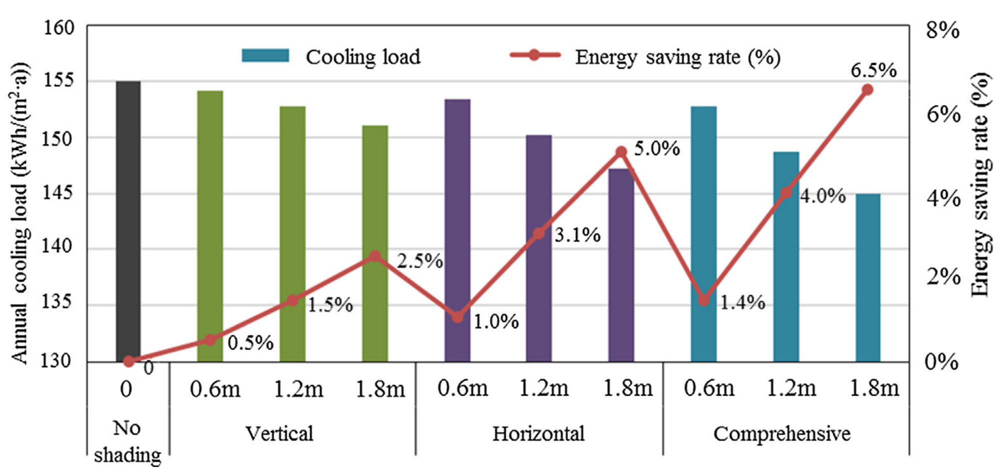

Fig. 8. Cooling loads with different scenarios under reference WWR (0.32).

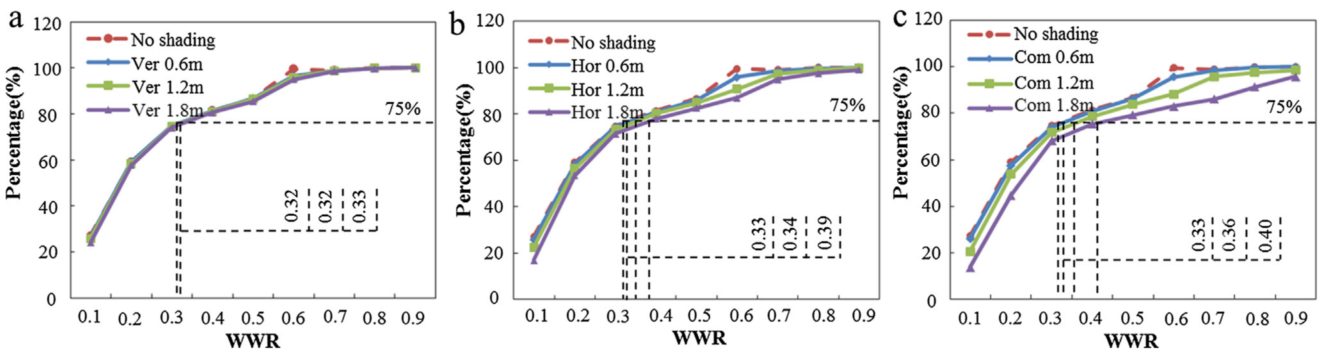

Fig. 9. Minimum WWRs under different sunshade configurations.

threshold of WWR increases with the sunshade length changing. As seen from Fig. 9, the minimum WWR for vertical sunshade stays the same and only raises to 0.33 at 1.8 m length. This may result from the diffuse daylight is less affected by the vertical sunshade under overcast climate. For horizontal sunshades, the minimum WWR raises to 0.33, 0.34 and 0.39 at 0.6 m, 1.2 m and 1.8 m length respectively. For the comprehensive sunshade, the minimum WWR raises to 0.33, 0.36 and 0.40 at 0.6 m, 1.2 m and 1.8 m length respectively.

3.5. Optimized WWR for all orientations with daylighting and energy requirements

Combining the result of both energy (Section 3.3) and daylighting performances (Section 3.4), the optimized WWR could then be ranged by the maximum and minimum value. This range indicates a better designed WWR for buildings with a certain sunshade configuration. Based on the same optimized process adopted for west-facing units in last two sections, all WWR ranges for other orientations are further studied, and the results are shown in Fig. 10.

From the figure, the optimized WWR for all orientations under different sunshade scenarios are drawn in red. Larger WWR values in blue indicate the building will consume more energy, while smaller values in grey reveal the buildings have poor daylighting performance. For all orientations, comprehensive sunshades offer the units with more WWR choice, while the vertical ones only offer a narrow range. For all sunshades, the south-facing units could have a wider WWR range for façade design. This may results from the building position which is located in the south of the Tropic of Cancer, and the accepted WWR for south-facing units with comprehensive sunshade could reach to 0.78.

Based on these results, the sunshade configuration could also be selected by WWR value in reverse. For example, if building WWR has already been decided as 0.5, then the sunshade of south units could be selected as horizontal 1.8 m, comprehensive 1.2 m or comprehensive 1.8 m from the figure. Further decision could be made based on the energy consumption and initial cost.

4. Discussion

Possible scenarios of WWR and sunshades have been proposed for Qionghai city, which is situated in south of the Tropic of Cancer. Before drawing conclusions, the importance of WWR for low latitude region will be further evaluated compared with other regions in Section 4.1.

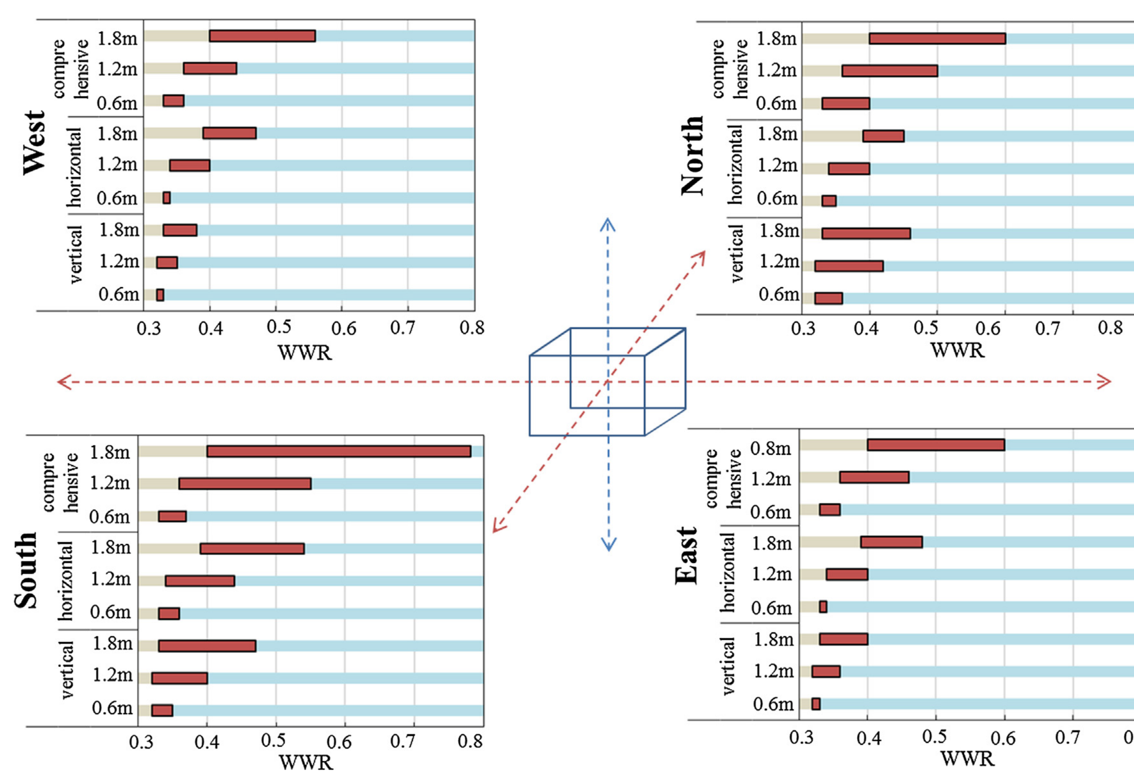

Fig. 10. Optimized WWR for all orientations with daylighting and energy requirements.

Table 3
Climatic features.

City	Location	Annual average temperature (°C)	Annual average humidity (%)
Qionghai	19.23°N, 110.47°E	24.5	85.5
Fuzhou	26.08°N, 119.28°E	20.3	75.9
Shanghai	31.54°N, 121.45°E	16.6	76.3

Based on possible scenarios, largest WWR condition will be examined and selected in Section 4.2.

4.1. Importance of WWR for energy performance in China low latitude region

To reveal the influence of WWR on energy performance, three weather conditions of coastal cities are selected for testing this hotel building (Table 3). As the other two cities do not need cooling all the year around, the simulation only compared for three high temperature months (June 1st–August 31th), and the results of north units are illustrated in Fig. 11.

As seen from figure, the cooling loads in all regions rises with the increase of WWR, and the building in low latitude has the largest cooling load. It could be recognized easily that the building with 0.3 WWR in Fuzhou will consume more energy than buildings in Shanghai with 0.9 WWR. While the cooling load in Qionghai almost equals to that in Fuzhou with 0.8 WWR. Obviously, the building in low latitude has a huge cooling load and it increase rapidly with the WWR. Therefore, WWR design is essential for energy performance and should be considered carefully in low latitude region.

4.2. Proposed WWR design for buildings in China low latitude region

Based on optimization process, accepted ranges of WWR with sunshades in each orientation have been proposed for hotel building in Qionghai. To make it more practical, WWRs are usually the same in all orientations for the same building, while the sunshade could be in different configurations. In this case, several cases are further built according to Fig. 10 and energy performances are examined in Table 4 and 5.

To meet the requirements of daylighting and energy-saving simultaneously, the largest WWR could be set as 0.55 for west-east-facing buildings with 1.8 m comprehensive sunshades. For south-north-facing buildings, 0.7 WWR could be reached with 1.8 m comprehensive sunshades.

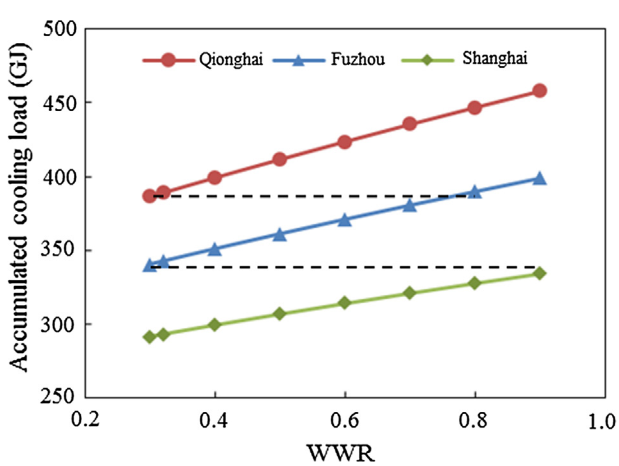

Fig. 11. Influence of WWR on cooling load in different regions.

Table 4
Energy performance of proposed facade scenarios for south-north-facing buildings.

Case	South			North			Annual cooling load (kWh/m^2)
	WWR	Sunshade	Length	WWR	Sunshade	Length	
1	0.5	Hor	1.8 m	0.5	Com	1.2 m	136.1 (< 140.2)
2	0.5	Com	1.2 m	0.5	Com	1.2 m	136.6 (< 140.2)
3	0.6	Com	1.2 m	0.6	Com	1.2 m	141.2 (> 140.2)
4	0.6	Com	1.8 m	0.6	Com	1.8 m	133.9 (< 140.2)
5	0.7	Com	1.8 m	0.7	Com	1.8 m	138.3 (< 140.2)
6	0.75	Com	1.8 m	0.75	Com	1.8 m	141.3 (> 140.2)

Table 5
Energy performance of proposed facade scenarios for west-east-facing buildings.

Case	West			East			Annual cooling load (kWh/m^2)
	WWR	Sunshade	Length	WWR	Sunshade	Length	
7	0.5	Com	1.8 m	0.5	Com	1.8 m	140.2 (< 155.0)
8	0.55	Com	1.8 m	0.55	Com	1.8 m	144.0 (< 155.0)
9	0.6	Com	1.8 m	0.6	Com	1.8 m	155.4 (> 155.0)

5. Conclusions

In this study, an early-stage facade design for a hotel building in China low latitude region is presented. The building cooling load in this low latitude area is much larger than other regions and increases rapidly with the WWR. Both daylighting and energy saving requirements are considered in optimization of WWR. The reference WWR is first decided based on the requirements of daylighting standards by using Radiance for standard room without external shading, and the value is 0.32 for all orientations. The annual cooling load of the whole building is then calculated by EnergyPlus based on the WWR condition. The results show west-east-facing buildings have a higher reference load as 155.0 kWh/m^2, while south-north-facing buildings have the reference value of 140.2 kWh/m^2.

To help optimize WWR, sunshades are adopted for block direct sunlight. Comprehensive sunshades have the best energy performance with the benefits of both horizontal and vertical ones. However, the energy saving is not equal to the horizontal ones plus vertical ones. Compared with reference value 0.32, the accepted WWR could reach to 0.56 for the west units with 1.8 m comprehensive sunshades.

The sunshades will decrease daylighting performance when blocking radiation, so the minimum WWR value should be set higher to meet the daylighting standard. All WWR ranges with different sunshade configurations in each orientation are calculated and the WWR range of south-facing units with 1.8 m comprehensive sunshade could range from 0.40 to 0.78. Based on these results, the sunshade design could be also selected based on WWR value with indoor thermal and luminous requirements.

To offer the biggest view to outside, the largest WWR for hotel buildings in China low latitude region could be set as 0.7 for west-east buildings and 0.55 for south-north buildings with 1.8 m comprehensive sunshades.

This work offers a verified workflow for optimizing WWR by considering both luminous and thermal requirements. Daylighting requirement decides the minimum WWR value, while energy consumption restricts the maximum value. In this paper, only different external shading types are integrated with buildings. However, this optimization process could be promoted to any other region and any other buildings with more kinds of façade configurations.

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References

[1] Minchen W, Siyuan C. Impact of spectral power distribution of daylight simulators on whiteness specification for surface colors. Color Res Appl 2018;43(1):27–33.
[2] Rea M, Figueiro M. Light as a circadian stimulus for architectural lighting. Light Res Technol 2016:1–14.
[3] Dai Q, Cai W, Shi W, Hao L, Wei M. A proposed lighting-design space: circadian effect versus visual illuminance. Build Environ 2017;122:287–93. [2017/09/01/].
[4] Littlefair P. Daylight sunlight and solar gain in the urban environment. Sol Energy 2001;70(3):177–85.
[5] Zhang W, Lu L, Peng J, Song A. Comparison of the overall energy performance of semi-transparent photovoltaic windows and common energy-efficient windows in Hong Kong. Energy Build 2016;128:511–8. [2016/09/15/].
[6] Huang Y, J-l Niu. Chung T-m. Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. Appl Energy 2014;134:215–28. [2014 12/1/].
[7] Xie JC, Xue P, Mak CM, Liu JP. Balancing energy and daylighting performances for envelope design: a new index and proposition of a case study in Hong Kong. Appl Energy 2017;205(Suppl. C):13–22. [2017/11/01/].
[8] Bueno B, Cejudo-López JM, Katsifaraki A, Wilson HR. A systematic workflow for retrofitting office façades with large window-to-wall ratios based on automatic control and building simulations. Build Environ 2018;132:104–13. [2018/03/15/].
[9] Xue P, Mak CM, Cheung HD. The effects of daylighting and human behavior on luminous comfort in residential buildings: a questionnaire survey. Build Environ 2014;81(0):51–9. [11//].
[10] Shen H, Tzempelikos A. Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading. Build Environ 2013;59:303–14. [2013/01/01/].
[11] Arumi F. Day lighting as a factor in optimizing the energy performance of buildings. Energy Build 1977;1(2):175–82. [1977/10/01/].
[12] Inanici MN, Demirbilek FN. Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey. Build Environ 2000;35(1):41–52. [2000/01/01/].
[13] Wen L, Hiyama K, Koganei M. A method for creating maps of recommended window-to-wall ratios to assign appropriate default values in design performance modeling: a case study of a typical office building in Japan. Energy Build 2017;145:304–17. [2017/06/15/].
[14] Alghoul SK, Rijabo HG, Mashena ME. Energy consumption in buildings: a correlation for the influence of window to wall ratio and window orientation in Tripoli, Libya. J Build Eng 2017;11:82–6. [2017/05/01/].
[15] Pino A, Bustamante W, Escobar R, Pino FE. Thermal and lighting behavior of office buildings in Santiago of Chile. Energy Build 2012;47:441–9. [2012/04/01/].
[16] Grynning S, Gustavsen A, Time B, Jelle BP. Windows in the buildings of tomorrow: energy losers or energy gainers? Energy Build 2013;61:185–92. [2013/06/01/].
[17] Su X, Zhang X. Environmental performance optimization of window–wall ratio for different window type in hot summer and cold winter zone in China based on life cycle assessment. Energy Build 2010;42(2):198–202. [2010/02/01/].
[18] Li DHW, Mak AHL, Chan WWH, Cheng CCK. Predicting energy saving and life-cycle cost analysis for lighting and daylighting schemes. Int J Green Energy 2009;6(4):359–70.
[19] Ghisi E, Tinker JA. An Ideal Window Area concept for energy efficient integration of daylight and artificial light in buildings. Build Environ 2005;40(1):51–61. [2005/01/01/].
[20] Li DHW, Cheung KL, Wong SL, Lam TNT. An analysis of energy-efficient light fittings and lighting controls. Appl Energy 2010;87(2):558–67. [2010/02/01/].
[21] Ochoa CE, Aries MBC, van Loenen EJ, Hensen JLM. Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. Appl Energy 2012;95:238–45. [2012/07/01/].
[22] Goia F, Haase M, Perino M. Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective. Appl Energy 2013;108:515–27. [2013/08/01/].
[23] Reinhart CF, Mardaljevic J, Rogers Z. Dynamic daylight performance metrics for sustainable building design. Leukos 2006;3(1):7–31.
[24] Nabil A, Mardaljevic J. Useful daylight illuminances: a replacement for daylight factors. Energy Build 2006;38(7):905–13. [7//].
[25] Mangkuto RA, Rohmah M, Asri AD. Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: a case study of buildings in the tropics. Appl Energy 2016;164:211–9. [2016/02/15/].
[26] Feng G, Chi D, Xu X, Dou B, Sun Y, Fu Y. Study on the influence of window-wall ratio on the energy consumption of nearly zero energy buildings. Proc Eng 2017;205:730–7. [2017/01/01/].
[27] Marino C, Nucara A, Pietrafesa M. Does window-to-wall ratio have a significant effect on the energy consumption of buildings? A parametric analysis in Italian climate conditions. J Build Eng 2017;13:169–83. [2017/09/01/].
[28] Ma P, Wang L-S, Guo N. Maximum window-to-wall ratio of a thermally autonomous building as a function of envelope U-value and ambient temperature amplitude. Appl Energy 2015;146:84–91. [2015/05/15/].
[29] Goia F. Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential. Sol Energy 2016;132:467–92. [2016/07/01/].
[30] Méndez Echenagucia T, Capozzoli A, Cascone Y, Sassone M. The early design stage of a building envelope: multi-objective search through heating, cooling and lighting energy performance analysis. Appl Energy 2015;154:577–91. [2015/09/15/].
[31] Xue P, Mak CM, Cheung HD, Chao J. Post-occupancy evaluation of sunshades and balconies' effects on luminous comfort through a questionnaire survey. Build Serv Eng Res Technol 2016;37(1):51–65.
[32] Singh R, Lazarus IJ, Kishore VVN. Effect of internal woven roller shade and glazing on the energy and daylighting performances of an office building in the cold climate of Shillong. Appl Energy 2015;159:317–33. [2015/12/01/].
[33] Shen H, Tzempelikos A. Daylight-linked synchronized shading operation using simplified model-based control. Energy Build 2017;145:200–12. [2017/06/15/].
[34] Ghosh A, Neogi S. Effect of fenestration geometrical factors on building energy consumption and performance evaluation of a new external solar shading device in warm and humid climatic condition. Sol Energy 2018;169:94–104. [2018/07/15/].
[35] Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, et al. EnergyPlus: creating a new-generation building energy simulation program. Energy Build 2001;33:319–31.
[36] CHN GB50033-2013. Standard for daylighting design of buildings; 2013.
[37] CHN GB/T 50378-2014. Assessment standard for green building; 2014.
[38] Yan QS, Zhao QZ. Building thermal process; 1986.
[39] CHN GB50189-2015. Design standard for energy efficiency of public buildings; 2015.